# A textural classification of argillaceous rocks and their durability

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ABSTRACT

Argillaceous rocks can display a wide range of durability behaviour after excavation and in cut slopes. In this paper we propose a classification of argillaceous rocks based on their textural characteristics. Three main components of the classification scheme are: the clastic framework, the fine-grained matrix and the cementing agent. Unlike other schemes, the unlithified argillaceous sediments are included as well. The names proposed for the rocks broadly follow the existing nomenclature used in petrographic classifications. The durability of some argillaceous rock types has been assessed by taking into account a set of degradation features of the excavated slopes. It has been observed that the ratios of these textural components exert a strong control on the long-term durability of slopes.

Key words: argillaceous rock, durability, slope deterioration, classification

## INTRODUCTION

Argillaceous rocks are frequent in the nature. They form around two thirds of the stratigraphic column (Blatt, 1982) and about one third of all rocks exposed at the earth surface (Franklin, 1983). Although strictly speaking an argillaceous rock is a rock made of clay, in its practical usage it has a broader meaning and it is equivalent to terms such as lutite or mudrock. It encompasses rocks such as argillite, claystone, siltstone, mudstone, shale, clay shale, or marl (Potter et al, 2005). They are all mostly siliciclastic rocks whose predominant constituent particles are silt and/or clay-size. Though argillaceous rocks are mainly composed of detritus from preexisting rocks, they may contain significant amounts of chemically precipitated cement (such as calcium carbonate, silica, iron oxide, among others).

The mineralogy of the argillaceous rocks is controlled by the source of the sediment and the conditions of the depositional environment. Typical clastic components are quartz, feldspar and phyllosilicates such as mica, chlorite, illite and other clay minerals. During diagenesis, compaction and cementation transform sediment into a rock. This is an ongoing process involving the progressive reduction of void space and the crystallization of authigenic minerals that results in an increase in strength and decrease in compressibility and permeability. This process is summarized by Czerewko and Cripps (2006).

It is difficult to assess when argillaceous sediment becomes rock because the conversion of sediment into rock is a continuous process. Soils are defined as natural aggregates of mineral grains that can be separated by gentle mechanical means such as agitation in water while rocks are natural aggregates of minerals connected by strong and permanent cohesive forces (Terzaghi and Peck, 1967). The soil-rock boundary is usually established based on their strength. British Standards (BS5930:1999) define a lower limit for the undrained shear strength of very stiff soils of 150 kPa and an upper unconfined compression strength for weak rocks of 12.5 MPa. Other limits have been proposed by other researchers (i.e. Hawkins, 2000). The boundary between hard soil and soft rock is commonly recognized around 1 MPa (Marinos, 1997; Czerewko and Cripps, 2006) although there is no complete agreement on this limit since these materials are part of a continuum (Johnston and Novello, 1993).

Argillaceous rocks display a contrasting behavior in construction works. Blasting is often required to excavate these rocks. However, the newly excavated slope surfaces may experience physical weathering and disintegrate in a very short span of time, over a period of months to years. The shallow, progressive, physical and chemical alteration of rock material and its subsequent detachment and removal or redistribution by transport agents is defined as deterioration (Nicholson, 2004).

Weathering predisposes the instability of the excavated slopes (Calcaterra and Parise, 2010). Although surface deterioration of cuts is perceived as having low risk it affects the safety of the users and involves costly maintenance works (Martínez-Bofill et al. 2004). Listric joints may develop parallel to the slope face being a main source of instability (Fig. 1). This type of discontinuities is seldom identified in boreholes or in field surveys as they develop mostly after the rock has been exposed. The exposed rock surface may experience swelling and breakdown facilitating the erosion and compromising the appropriate performance of the remedial and/or stabilization measures (Fig. 2). When interbedded layers of limestone, sandstone or conglomerate are present, disaggregation of the argillaceous rock results in overhangs, which may produce topples and failures, especially if vertical joints parallel to the slope face exist (Fig. 3).

Figure 1. Slope surface deterioration with the development of listric (curvilinear) failures on mudstones in the C-17 road at Tona, Barcelona province, NE Spain.

Figure 2. Cutslope surface deterioration in the N-1 road at Ormaiztegi in the Gipuzkoa province, N Spain. The argillaceous rock decomposes around the bolt thus preventing its proper operation.

Figure 3. Differential weathering along the C-16 road at Navàs, Barcelona province, N Spain. Spalling and disaggregation of the mudstone have generated overhangs in the sandstone layers which eventually fall.

The described behavior cannot be generalized and some road cuts in argillaceous rocks may remain virtually unweathered without signs of degradation for years (Figure 4).

Figure 4. Slightly deteriorated cut slope. Well preserved blast holes are observable several years after the excavation of the slope in the C-17 road at Torello, Barcelona province, NE Spain.

This contrasting behavior has attracted the interest of engineers involved in the design, construction and maintenance of embankments, road cuts and tunnels. In fact, most the maintenance cost is due to the inability to accurately identify and classify these rocks, and anticipate their behavior.

## CHARACTERIZATION OF THE ARGILLACEOUS ROCKS FOR ENGINEERING PURPOSES

Many attempts have been made to classify and characterize the argillaceous rocks in order to predict their behavior. Classical soil analyses such as particle size and Atterberg limits are not appropriate for characterizing the argillaceous rocks because they cannot be easily disaggregated. Porosity, degree of saturation and fissuring are parameters that govern the strength and deformability of the argillaceous rocks. Similarly to other rocks, the Uniaxial Compressive Strength (UCS) tends to increase with the increase of packing density. Recent reviews on the wide range of properties and on the engineering performance of stiff sedimentary clay were prepared by Chandler (2010), Simpson (2010) and Pineda et al (2014). Weathering of the argillaceous rocks reduces UCS and shear strength (Taylor, 1988; Bhattarai et al. 2006). Czerewko and Scripps (2006) summarized the variation of the mudrock properties with the different stages of the diagenetic maturity. Despite all this work, several researchers have reported that standard rock tests are unsuitable to properly characterize the long-term behavior for most of argillaceous rocks and its durability (Czerewko & Cripps, 2006; Nickmann et al. 2006, 2010). The reason is that routine geomechanical tests are oriented to determine rock strength or the capability to withstand loads but they are not primarily focused to assess the susceptibility of the rock to weaken upon exposure and disintegrate along time. In other words, they are not designed to assess the durability.

The durability of a rock expresses its ability to resist abrasion, wear and breakdown with time (Santi, 1998). There exist several converging points of views on the factors that govern durability of the argillaceous rocks and mechanisms leading to slaking and dispersion of soil particles. Among them stand the swelling produced by stress release and water absorption (Mitchel, 1993). After excavation stress release results in the development of fissures. These microstructures, rock pores and fissures induce the infiltration and evaporation of water (cycles of wetting and drying) with the subsequent volume changes that produces the slaking of the rock.

Compaction and cementation are critical post-depositional processes that control the properties and long-term behavior of the argillaceous rocks (Morgenstern et al 1974; Dick and Shakoor, 1997). In the first stages of diagenesis, materials are poorly indurated and have a strong tendency to disaggregate upon immersion in water. The prominent role of bonding on durability was highlighted by Mead (1936) and Underwood (1967), who classified shales into two broad groups. The first includes the compacted shales (mudrocks) which have been consolidated by the weight of the overlying sediments without intergranular cement. Meteoric agents may return the consolidated argillaceous rock to an assemblage of minerals and rock fragments. The second group includes cemented shales (mudrocks) that have a cementing agent (calcareous, siliceous or ferruginous) or bonding material formed by recrystallization of clay minerals which reduce porosity and enhance durability by preventing the entrance of water and air. The removal of cement as well as the poor binding efficacy may become a cause for rock degradation.

The role of the stress history of the argillaceous rocks in controlling both the fabric and bonding of the rock and explaining its mechanical behavior has been summarized by Alonso and Pineda (2006) and Gens (2013). Bjerrum (1967) attributed the swelling of unloaded shales to release of the locked in strain energy of the diagenetic bonds. The less indurated clays will more readily release the strain energy stored during compaction

The fundamental influence of the mineralogy has been also discussed by several authors (Gökçeoglu et al. 2000; Sadisun et al 2005). Russell (1981) observed the low durability of shales was partly due to the inefficient cementing by calcite. Instead, the presence of hard bands, shaly limestone, increased significantly the durability. The strength of fine-grained argillaceous rocks is found inversely related to the total percentage of clay minerals (Gökçeoglu et al. 2000; Ward et al. 2005) while the presence of expandable minerals such as smectites (Czerewko et al. 2006), or sulfides (Quigley & Vogan 1970; Grattan-Bellew and Eden 1975; Sadisun et al. 2005) enhances the response to changes in moisture content or changes in pore water chemistry. High carbonate content is associated to the high durability of the rocks (Gökçeoglu et al. 2000). In most of these studies the influence of the mineralogical content on the durability of the rocks has been established by means of statistical relations. However, neither a precise nor the quantitative proportions of the mineralogical constituents governing the durability have been proposed so far.

Most widely-used tests to assess rock durability are the Slake Durability Test (SDT) (Franklin and Chandra, 1972) or the Jar Test (Wood and Deo, 1975) which aim at determining the effects of alternate drying and wetting on the durability of soil and rock. Although these tests may be useful for assessing the short-term performance of certain argillaceous rocks, the extensive experience on their performance indicates that their results are far from yielding fully satisfactory results in the characterization of the long-term durability of argillaceous rocks (Nickmann et al. 2006). This is attributed to the fact that durability is not dependent on a single property but on combination of parameters such as the porosity, compressive strength (expression of the bond strength of the matrix), grain size distribution, texture (grain or matrix supported), mineralogical constituent, degree of cementation and stress history (Santi, 1998; Cripps et al. 2006; Nickmann et al. 2006; Martínez-Bofill, 2011).

## A CLASSIFICATION SCHEME FOR ARGILLACEOUS ROCKS

The successful construction and performance of engineering works in argillaceous rocks depends on correctly anticipating the long-term behavior of these particular materials. As discussed above, conventional laboratory tests often prove to be unable to fully characterize durability while the search for predictors of the long-term behavior of the weak rocks after their exposure is still a challenge.

The mineralogy (Grainger, 1983), particularly expansive clays (Dick, 1992; Dick and Shakoor, 1992) and the cementation (Shakoor and Brock, 1987) are widely accepted as important factors controlling the deterioration of the rock cuts. Consequently, it might be possible to establish a relationship between the mineralogical constituent, the cement content and the durability of the argillaceous rocks. The names of sediments and sedimentary rocks have been traditionally proposed based on a wide range of criteria such as the mineral content, texture, and other physical attributes as well as the depositional environment, genetic relationship and economic importance (Hallsworth and Knox, 1999). However, as stated by Gens (2013), a shortcoming of classifications based only on grain size is that they give no information on the intensity of bonding or lithification, which is an important aspect in the context of durability. In order to overcome these drawbacks we present a new classification scheme for the argillaceous rocks.

A classification should meet the needs of providing a concise and systematic method for designating various types of rocks, and, if engineering properties are important, the classification should also enable to derive soil properties. The proposed classification scheme is based on the rock texture which specifically accounts for the bonding constituent. This classification does not attempt to replace the existing and widely accepted terms. It also does not intend to change the established proportions of the constituents of the argillaceous rocks and soils. Only when several options exist, we have selected the most appropriate one.

The previously proposed classification involving argillaceous rocks are first reviewed, retaining their original terms. Traditionally, sediments and sedimentary rocks have been classified independently and do not take into account of schemes for other sediments and rocks with which they overlap. Thus, limestone, sandstone and ironstone are classified separately although in nature they share strong compositional and genetic links. Furthermore, the criteria used to classify each sedimentary group are usually different. As a result, terms of sediment and sedimentary rocks tend to be inconsistent and lacking in basic or general guidelines (Hallsworth and Knox, 1999). Many classification schemes of detrital sediments and rocks have been proposed. Hallsworth and Knox (1999) and USGS (2004) presented complete reviews of the existing classification schemes which will be taken as starting point.

Krynine (1948) used rock texture, including mineralogical content as criteria for classification. Grain size was the primary criterion for grouping conglomerates, sandstones and fine clastics. Williams et al. (1982) presented a ternary plot naming conglomerates and sandstones those clastic rocks having respectively more than 50% of coarse fraction (pebbles and cobles) and sand. Folk (1954, 1980) based his classification on the particle size (Figure 1). In his ternary plot the vertices are gravel, sand and mud. He proposed the term conglomerate when gravels content exceed 80% and several combinations of the terms gravel, sand and mud (silt and clay). This scheme has been widely accepted.

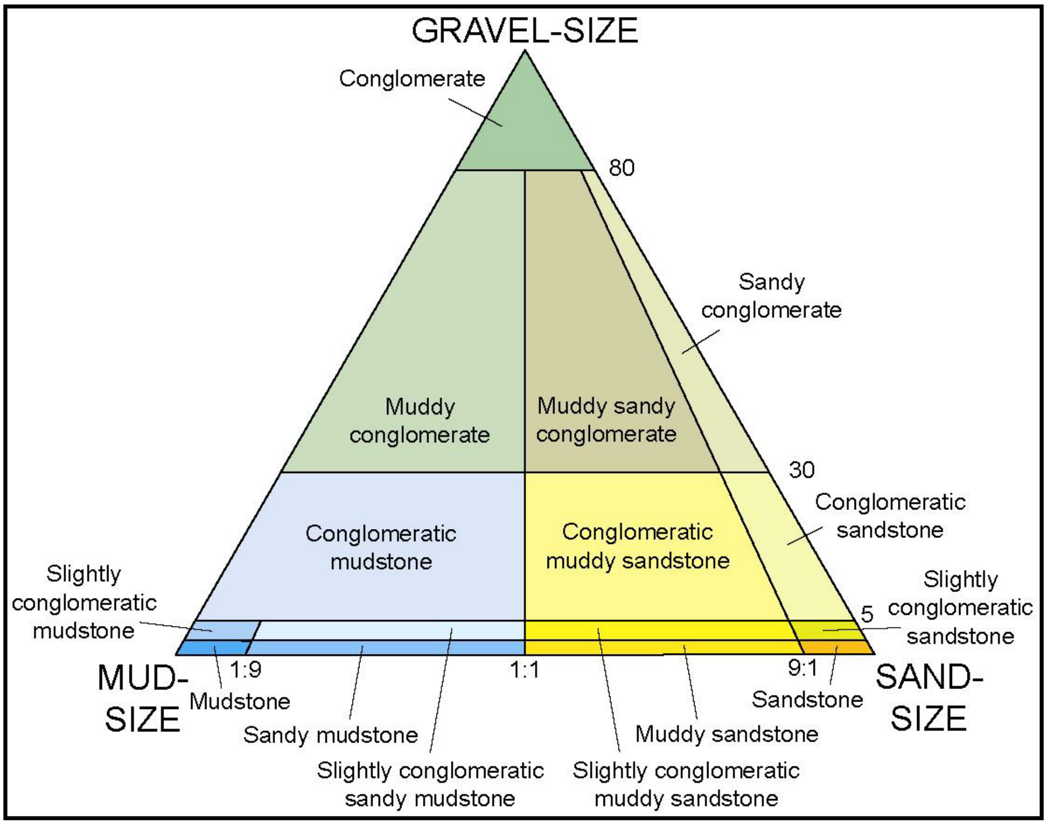


Fig.5 Classification of sedimentary detritic rocks (from Folk, 1954)

Pettijohn et al. (1972) adapted Krynine's (1948) classification and introduced the term fine matrix to distinguish between arenites and mudstones. Rock with more than 75% of fine-grained content (<0.03mm) is named mudstone. Rocks with contents between 15 and 75% of fine particles are named wackestone. Sand size aggregates with fine-grained content less than 15% (this boundary is 10% in the proposal of the USGS 2004) correspond to sandstones.

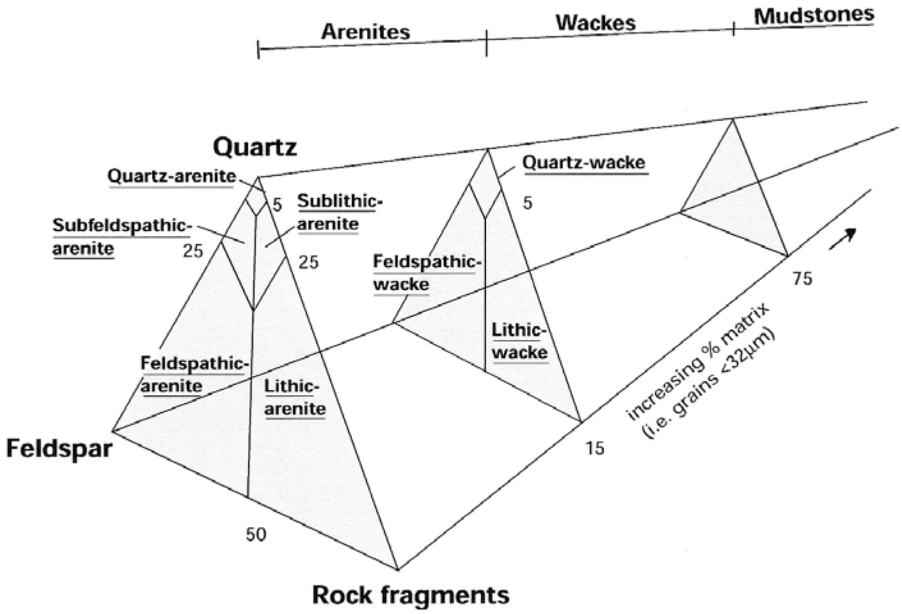


Figure 6. Classification of the arenaceous rocks from Pettijohn et al. 1972 in USGS (2004).

On the other hand, carbonatic sediments and rocks (limestone, dolomite) are defined as having more than 50% of carbonate content. This percentage must not include the carbonatic cement although this requirement is not necessary in the classification of the USGS (2004).

Several researchers suggest that the classification of the argillaceous rocks based on particle size and mineralogical composition may not be appropriate due to the difficulty of separating the individual grains from each other (Czerewko et al. 2006).

We propose a new classification, based on textural attributes of the argillaceous rocks. The nomenclature consists of root names which combine information on grain size (grain framework, matrix) and the amount of cementing agent. To classify a sample, one needs to determine the content of clastic framework (sand size), matrix and cement.

The proposed scheme (figure 7) is based on a ternary plot in which the vertices are sand-size content (between 0.032 and 2mm), mud-size content (< 0.032mm) and cement (calcium carbonate). The boundary of 0.032mm is the one proposed by Dott (1964), Hallsworth and Knox (1999), and USGS (2004). It is also found as practical boundary for visually identifying individual grains using a petrographical microscope. Smaller sized grains often appear overlapped in thin sections and may be subjected to misinterpretations.

The scheme includes the boundary proposed by Dott (1964) between arenites, mudstones, and wackes. The latter are however considered arenaceous rocks. Despite this apparent inconsistency we have included wackes in the classification of the argillaceous sediments because most of wackes are classified as shales or mudstones in the field and because in the classification of terrigenous sediments, Folk (1954), adopted by USGS (2004) the boundary between of mudrocks and sandy rocks corresponds to a relative proportion of 50% of mud-size constituents.

We have adopted the same criterion as USGS (2004) for the compositional attribution of the grain-size framework. No distinction has been made on whether the grain framework is mostly siliciclastic, carbonate or other.

The argillaceous rocks may contain authigenic minerals formed during the diagenesis at temperatures and pressures less than that required for the formation of the metamorphic rocks. In this classification of the argillaceous rocks, the authigenic minerals may correspond to the anchimetamorphism that is the final stage of the deep diagenesis or the first effects of metamorphism. (Kornprobst, 2003).

The term mud and mudstone is given to sediments and rocks containing at least 75% of fine grained constituent. Mixtures of mud with sand with the former ranging between 75% and 15% are named wackes. The predominance of fine components (up to 65%) or sandy components (up to 60%) qualifies wackes as muddy wacke or sandy wacke respectively.

Cement is the textural constituent of the proposed classification not considered in other classification schemes. Cement is a fundamental rock constituent that determines the strength and makes the difference between soils and rocks. Cement is usually calcium carbonate (calcite) or calcium magnesium carbonate (dolomite). However, cementing agents of a different composition (i.e. silica, iron oxide) may also be present.

The proposed classification (Figure 7) establishes the boundary between sediments and rocks ranging between 4% and 15% of cement content. This boundary is defined based on the recommended percentages of cement used in soil stabilization (ACI, 1997, USACE, 1994). At the other extreme of the plot, a 48% of cementing agent content has been taken to define the boundary between detritical rocks and chemical sedimentary rocks. This value of 48% is the porosity of a simple cubic packing of identically–sized spheres (Conway and Sloane, 1993) in which cement may grow. In chemical sedimentary rocks, the cementing agent can be found not only as a post-sedimentary phase, but also having been formed during the sedimentation.

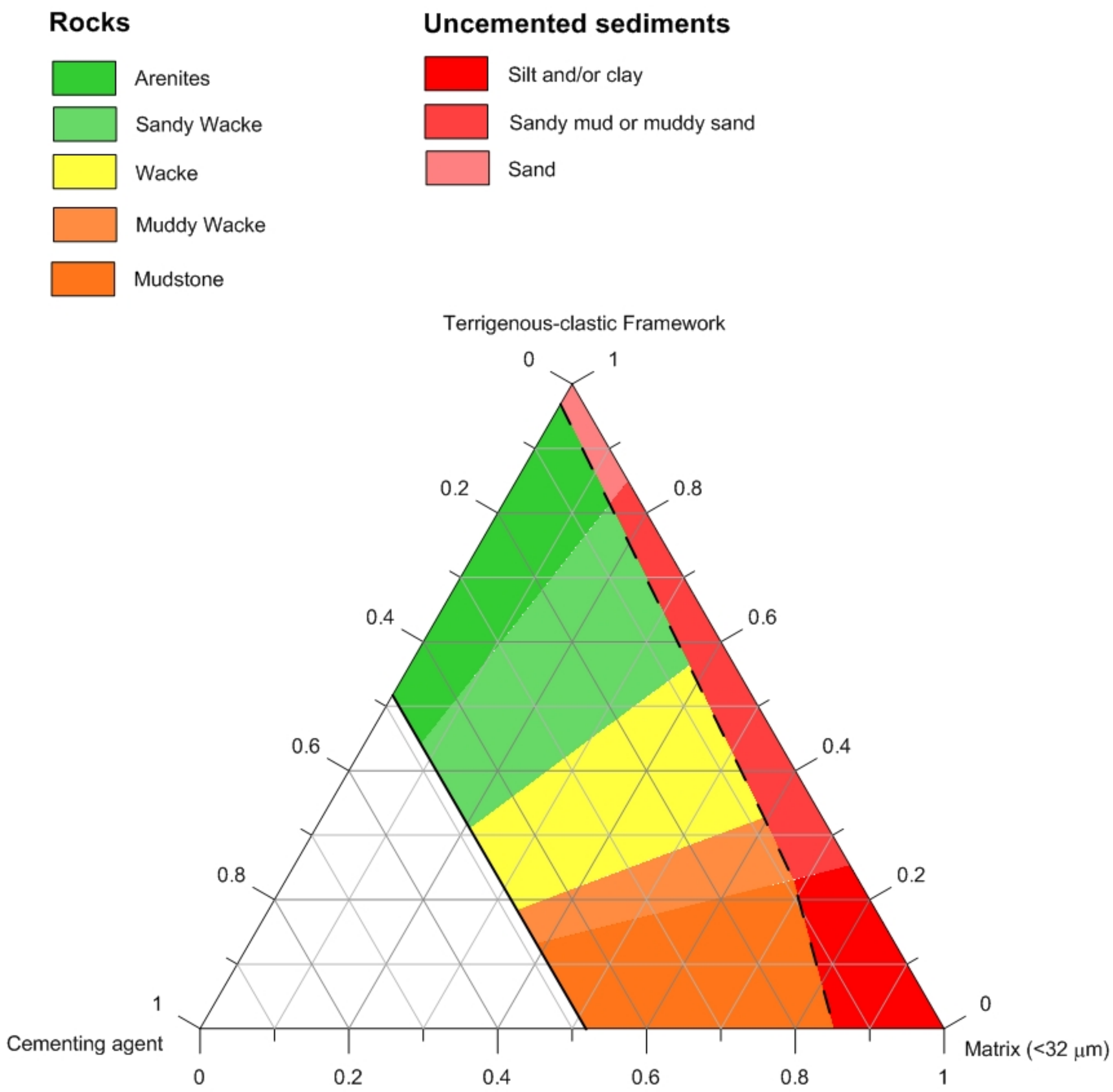


Figure 7. Proposed textural classification of the argillaceous rocks

The mineral composition of terrigenous-clastic constituents can be determined reliably with the petrographic microscope and by X-ray diffraction. Fine matrix has a size smaller than 32µm and may be identified in the microscope as well. However, distinction between matrix and cement can be only achieved if the cement crystals are bigger than 32µm (i.e. sparite in carbonate cemented rocks). Smaller crystals (microsparite and micrite) are unresolvable for quantitative analysis with the petrographic microscope and the cement cannot be distinguished from the matrix. In this case, the amount of cement may be determined with a procedure such as the one described below.

## QUANTIFIYING THE CONSTITUENTS OF THE ARGILLACEOUS ROCKS

Determining the components of the proposed classification scheme is not straightforward, because they cannot be mechanically separated. Furthermore, the grain size of both cementing agent and fine matrix are often unresolvable using a petrographic microscope. The fine grained cement cannot be distinguished from the matrix thereby requiring an alternative procedure to separate the two constituents.

X-ray Fluorescence (XRF) and X-ray Powder Diffraction (XRD) are the techniques most frequently used to determine the constituents of the argillaceous rock. XRF yields the chemical composition of the rock as oxides of the different elements (Potts, 1992). This composition relates to the mineralogy but it does not provide the real mineralogical species of the rock. For example the CaO content may correspond to calcite, dolomite or Ca silicates (plagioclase), which may be either part of the detrital constituents of the rock (calcite fragments and/or carbonated fossils), or cementing agent, or both.

The XRD is a rapid analytical technique used for mineral identification of a crystalline material (Bish & Post, 1989). The mineralogical content of the rock can be determined by the semi-quantitative Rietveld analysis of X-ray powder diffraction, determining the amount of each mineral (Young, 1993). The Rietveld XRD permits the accurate determination and quantification of the mineral species present in the rock although no information is provided on whether these minerals are part of the terrigenous framework or of the fine-grained matrix.

In order to overcome this uncertainty, we performed the following procedure (Figure 8) developed for rocks containing carbonate cement (Martínez-Bofill, 2011). The procedure may be adapted for the quantification of the components of the argillaceous rocks indurated with other cementing agents:

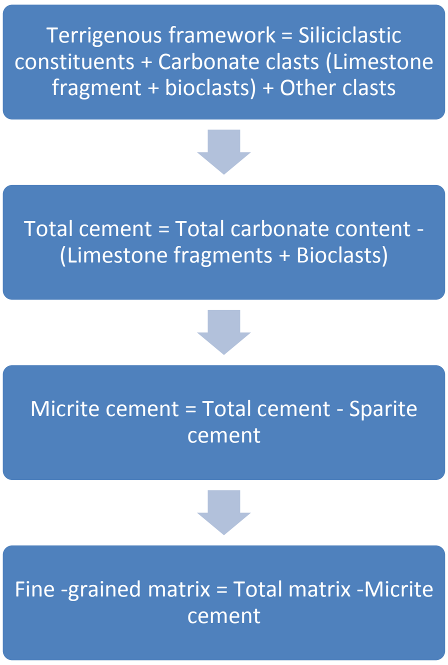


Figure 8. Procedure for determining the textural components of the argillaceous rocks (see explanations in the text)

First, the terrigenous clastic framework, the matrix content and sparite cement (>32µm) are determined in the optical microscope on thin sections of rock samples, provided with a point counter. Between 1000 and 2000 counts per section are recommended to be performed. Mineral constituents are obtained by counting each mineral occurrence along a series of traverse line across the thin section (Figure 9).

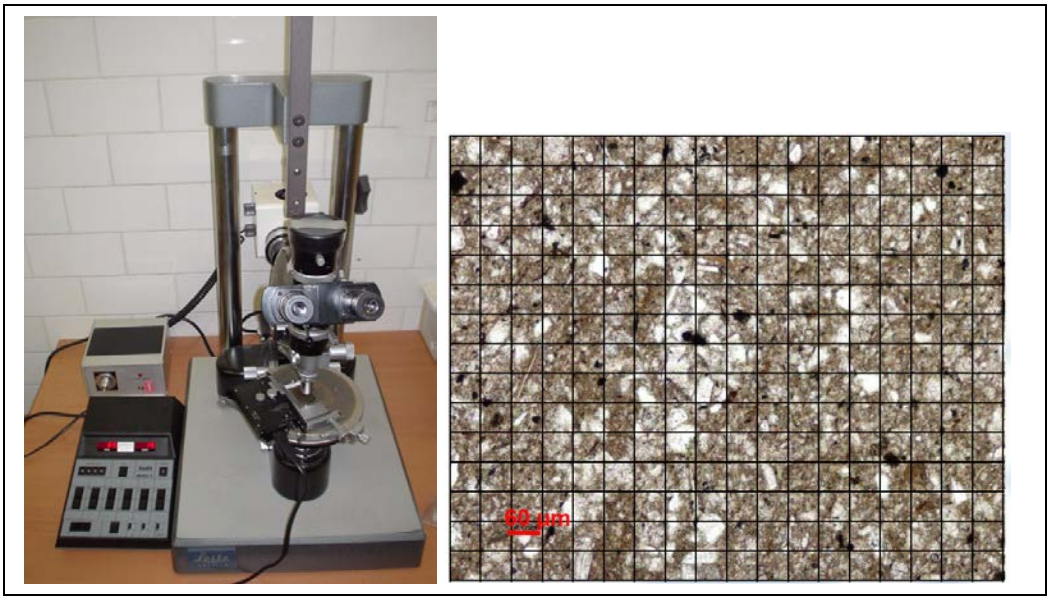


Figure 9. Determination of the clastic framework, matrix and cement bigger than 32µm in the petrographic microscope (see explanation in the text).

All clasts are identified and counted using the polarizing microscope. The terrigenous framework is mostly composed of siliciclastic constituents although it may contain clasts of calcium carbonate composition (i.e. limestone fragments, bioclasts). The terrigenous framework is then divided between carbonate clasts (limestone fragments, bioclasts) and the rests (mostly quartz, feldspars and lithic fragments).

The total amount of carbonate content of the sample is determined with the Bernard calcimeter method (UNE-103-200:93, ASTM D4373). The total carbonate content includes both carbonate clasts and carbonate cement. By subtracting the amount of carbonate clasts from the total carbonate, the total amount of cement is obtained. The latter is composed of sparite carbonate crystals (>32µm) and microsparite and micrite (<32µm) which are included within the matrix. The micrite content which is unresolvable with the petrographic microscope is obtained by subtracting the sparite content from the total cement.

The fine-grained matrix contains all constituents smaller than 32µm including the micritic cementing agent. The amount of silt and clay (mud) constituents is obtained by subtracting the microsparite and micrite content from the total amount of matrix.

This procedure has been complemented when necessary by the Rietveld XRD. The latter is particularly useful for double-checking the total calcium carbonate content measured with the Bernard calcimeter (table 1) and for obtaining the composition of rock samples mostly composed of fine matrix, in which the mineralogical constituents are unresolvable using a petrographic microscope.

| **Sample** | **% $CO_2$ Calcimetry** | **% $CO_2$ Calcite XRD Rietveld** | **% $CO_2$ Dolomite XRD Rietveld** | **Difference Calcimetry- XRD** |
|---|---|---|---|---|
| **A-2.1 m1** | 28,84 | 31,19 | 0,65 | -3 |
| **A-2.1 m2** | 5,1 | 3,97 | 1,94 | -0,81 |
| **A-2a.2** | 6,73 | 0 | 8,3 | -1,57 |

| | | | | |
|---|---|---|---|---|
| **A-2.3** | 19,57 | 16,93 | 2,76 | -0,12 |
| **A-2.5** | 19,57 | 16,24 | 2,65 | 0,68 |
| **A-2.6** | 30,44 | 29,59 | 2,16 | -1,31 |
| **A-2.7** | 21,59 | 9,13 | 11,59 | 0,87 |
| **A-2.8** | 27,79 | 0 | 34,8 | -7,01 |
| **C-16.1 m1** | 15,57 | 13,23 | 1,65 | 0,69 |
| **C-16.2** | 14,77 | 13,89 | 1,81 | -0,93 |
| **C-16.3** | 13,94 | 12,77 | 0 | 1,17 |
| **C-16.4 m1** | 18,56 | 16,41 | 0,68 | 1,47 |
| **C-16.4 m2** | 8,49 | 8,11 | 1,63 | -1,25 |
| **C-16.4 m3** | 23,83 | 21,43 | 0,37 | 2,03 |
| **C-16.6** | 17,9 | 15,32 | 0,6 | 1,98 |
| **C-16.7** | 9,81 | 7,2 | 2,77 | -0,16 |
| **C-17.1** | 16,75 | 15,87 | 3,85 | -2,97 |
| **C-17.2** | 16,91 | 16,59 | 2,87 | -2,55 |
| **C-17.3** | 15,21 | 13,63 | 2,19 | -0,61 |
| **C-17.4** | 8,66 | 7,77 | 4,91 | -4,02 |
| **C-17.5** | 17,21 | 13,64 | 3,2 | 0,37 |
| **C-25.1** | 23,83 | 21,02 | 1,62 | 1,19 |
| **C-25.2** | 13,81 | 12,79 | 2,94 | -1,92 |
| **C-25.3** | 18,81 | 15,34 | 2,81 | 0,66 |
| **C-25.4 m1** | 16,44 | 13,6 | 1,59 | 1,25 |
| **C-25.4 m2** | 17,32 | 17,25 | 1,39 | -1,32 |
| **C-25.5 m1** | 8,18 | 8,28 | 0,77 | -0,87 |
| **C-25.5 m2** | 8,09 | 7,8 | 2,59 | -2,3 |
| **C-25.7 m1** | 17,32 | 19,47 | 0,91 | -3,06 |
| **C-25.7 m2** | 22,73 | 16,97 | 1,39 | 4,37 |
| **C-25.9** | 13,06 | 12,49 | 3,02 | -2,45 |
| **C-25.10** | 18,64 | 11,3 | 8,7 | -1,36 |

| | | | | |
|---|---|---|---|---|
| **C-25.11** | 15,84 | 9,53 | 0,81 | 5,5 |
| **C-25.12 m1** | 10,04 | 10,32 | 2,3 | -2,58 |
| **C-25.12 m2** | 11,62 | 9,36 | 0,89 | 1,37 |
| **C-25.13** | 18,82 | 12,4 | 3,33 | 3,09 |
| **C-25.14 m1** | 34,93 | 21,5 | 1,35 | 12,08 |
| **C-25.15 m1** | 36,62 | 29,91 | 1,24 | 5,47 |
| **C-25.16** | 16,66 | 12,32 | 2 | 2,34 |
| **C-25.17** | 2,2 | 0 | 0 | 2,2 |
| **C-55.1 m1** | 23,82 | 23,63 | 0,68 | -0,49 |
| **C-55.1 m2** | 15,77 | 13,31 | 1,63 | 0,83 |
| **C-55.1 m3** | 16,21 | 12,18 | 1,3 | 2,73 |
| **C-154.1 m1** | 25,41 | 28,37 | 1,62 | -4,58 |
| **L-301.1 m1** | 10,95 | 5,82 | 4,31 | 0,82 |
| **L-301.2 m1** | 20,57 | 13,45 | 1,25 | 5,87 |
| **L-301.2 m2** | 17,94 | 14,94 | 1,14 | 1,86 |

Table 1. Total carbonate content of samples collected in different cut slopes in Spain (see next section) measured with the Bernard calcimeter and the amount of calcite and dolomite obtained with X-ray difractometry. Differences are usually less than 5%.

## PERFORMANCE OF THE CLASSIFICATION

The performance of this classification has been assessed by analyzing the mid/long-term behavior (between 2 and 30 years) of cut slopes excavated in different argillaceous rock formations of Catalonia and Basque Country, in Spain.

The analysis consists of confronting the qualitative description of the deterioration features of the cuts (taking into account the time of exposure) with both the Slake Durability Index (SDI) and the textural composition of intact rock samples collected in the cuts. The cutslopes were first grouped based on their deterioration stage. Contrary to other schemes aiming at assessing the susceptibility to deterioration (i.e. Nicholson, 2004), grouping of the cut slopes is only descriptive and based on the present state of the slope face. The deterioration stages are defined using the following descriptors (Martínez-Bofill et al. 2004) (Figure 10):

| Cutslope | Comment |
|---|---|
|  | Stage 1<br><br>More than 20 years old cutslope composed of sandstones in the C-17 road at Borgonyà, Spain.<br><br>Drill holes are still observable in the excavated rock surface |
|  | Stage 2<br><br>More than 20 years old cutslope in the C-17 road at Borgonyà, Spain.<br><br>Rock chips (few cm length) fall from the slope surface and scattered failures of rock blocks. Chips accumulate at the bottom of the slope without further slaking.<br><br>Failures governed by pre-existing tectonic joint are not considered deterioration features |

| | |
|---|---|
|  | Stage 3<br><br>10 years old cutslope in the C-17 road at Malla, Spain<br><br>Mid-term deterioration of the excavated slope composed of mudstones. Tendency of slope recession and frequent block failures (listric failures). Rock chips tend to break apart decomposing up to sand-size. |
|  | Stage 4<br><br>6 years old cutslope composed of mudstones in the C-25 road at Gurb, Spain<br><br>Tendency to form regolith at the excavated surface |
|  | Stage 5<br><br>2 years old cutslope in the C-25 road at Fontfreda, Spain<br><br>Slope composed by poorly indurated silts and clays |

Figure 10. Deterioration features observed in selected excavated slopes. The period of time during which these deterioration features are generated reduces from Type 1 to Type 5.

- Stage 1: Intact cutslope. Blast holes are fully visible. Intact or virtually intact excavated slope surface. The slope is stable and only sporadic rockfalls occur.
- Stage 2: Slightly weathered slope surface. Fissures and spheroidal exfoliation cracks may appear after some years. It is an overall stable slope. Local (small size) rockfalls occur associated to scattered listric joints. Blast holes are observable for most of the length. The original profile of the excavated slope is kept in average. Unweathered rock chips of a few centimeters in length may accumulate at the bottom of the slope
- Stage 3. Weathered slope surface. The excavated surface loses the rocky appearance with time. Spalling and disintegration of the rock surface takes place in less than 10 years. Blast holes are poorly preserved. Frequent small size slides and falls occur through listric joints (curved) generated after the excavation. Debris starts accumulating at the slope foot. The accumulated material decomposed up to sand size and rarely to smaller sizes. Generally overall stable but receding slope.
- Stage 4. Heavily weathered slope surface. Intense slaking of the rock surface and tendency to form regolith. Continuous slaking and falling of chunks prevents the slope from rock falls. Weathered rock surface (regolith) may reach depths of some decimeters (figure 11). Original rock structure cannot be recognized. Blast holes have virtually disappeared. Erosion and gullying of the slope surface. Fallen debris easily decomposes to silt-clay size fragments. Receding slope profile. Steep slopes tend to be unstable.
- Stage 5. Slope composed of poorly indurated silt and clay. The original rock color has vanished. Weathering and cracking of the rock reach depths of more than 25 cm. Steep slopes are unstable with frequent rotational failures. Gullying develops even with low slope angles.

In this description, the slope failures generated along pre-existing joints in the rock mass were not considered as rock deterioration features.

Figure 11. Gully of more than 20cm depth in the regolith developed on the surface of a 6-years old excavated slope of the C-25 road at Gurb, Spain (stage 4)

Seventy-two rock samples were collected from forty-three excavated slopes. The samples were extracted with a portable drilling machine. Cores of 30 mm diameter and 30 cm length were obtained and sent to the laboratory for mineralogical and textural characterization. For the selection of the slopes and the rock samples we took into account several factors: (i) presence of either marine or continental formations; (ii) lithological variety such as mudstones, marls, and shales, in order the assess the influence of the mineralogical and textural components; (iii) absence or a low degree of structural deformation of the layers and whenever possible, the presence of expandable clays to avoid the inclusion of factors that may generate additional scattering in the assessment of the durability of the materials.

The samples cover a wide range of argillaceous rock compositions and the results are presented in Figure 12. As mentioned above, the procedure to quantify the textural components is subjected has some of uncertainty due to of the assumptions made for the quantification of the cementing agent. Therefore, the mineralogical content has been replicated by performing a semi-quantitative Rietveld analysis by X-ray powder diffraction (Martínez-Bofill, 2011). It is noticeable that despite most of the samples having been classified in the field as mudstones and shales only a few of them fulfill the requirement of having more than 75% of fine-grained constituents.

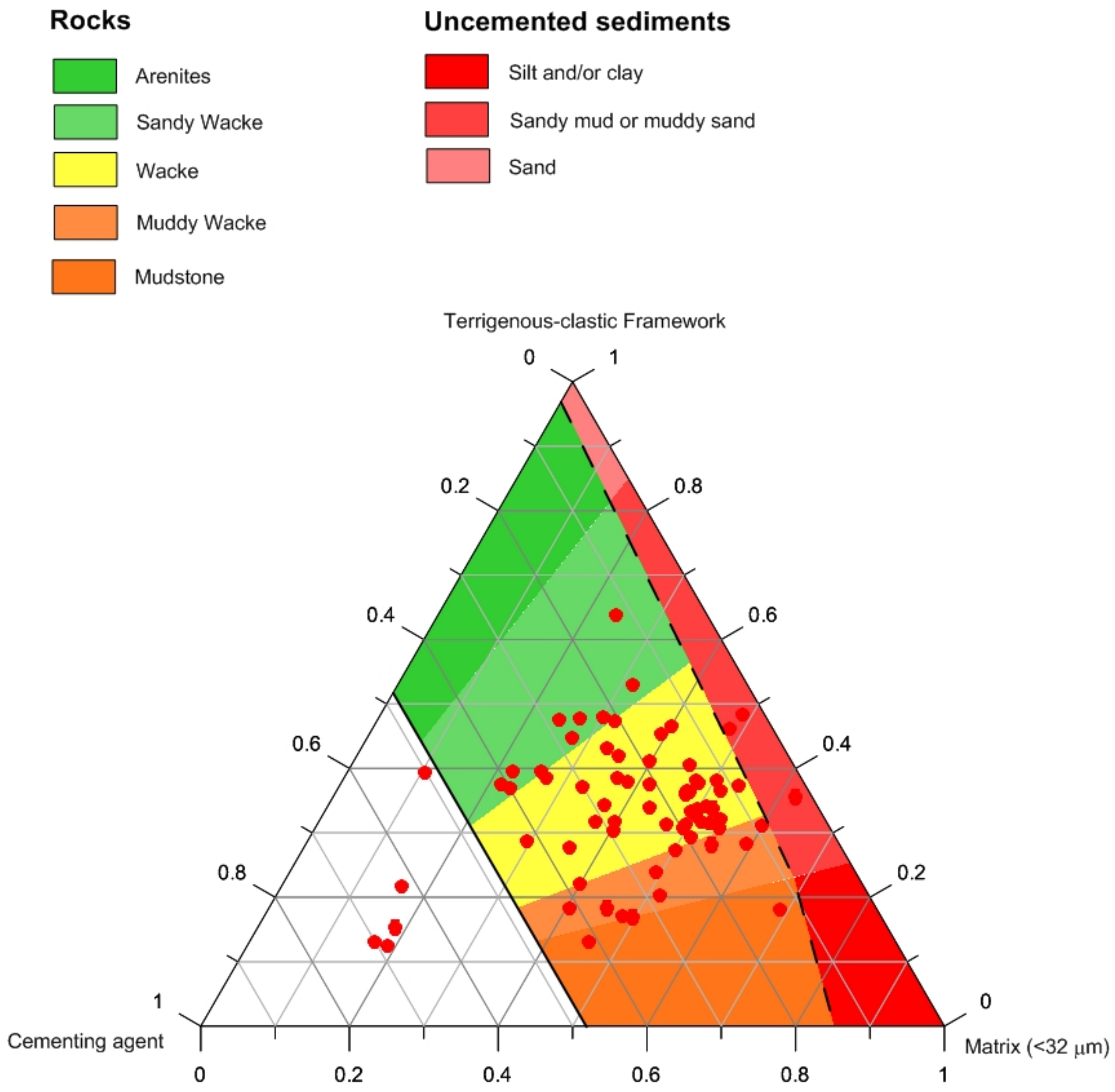


Figure 12. Textural content of the collected samples using the classification scheme proposed in this paper

The main textural feature that can be identified at first sight during the microscope observation or even at nude eyesight in the counterlight is the homogeneity. Samples may be homogeneous or heterogeneous (Martínez-Bofill et al. 2008): homogeneous textures are characterized by a regular and uniform grain-size and matrix distribution, without remarkable disturbing signs (Figure 13). Conversely, heterogeneous textures show a pattern of different types of textures and grain-size distribution (Figure 14).

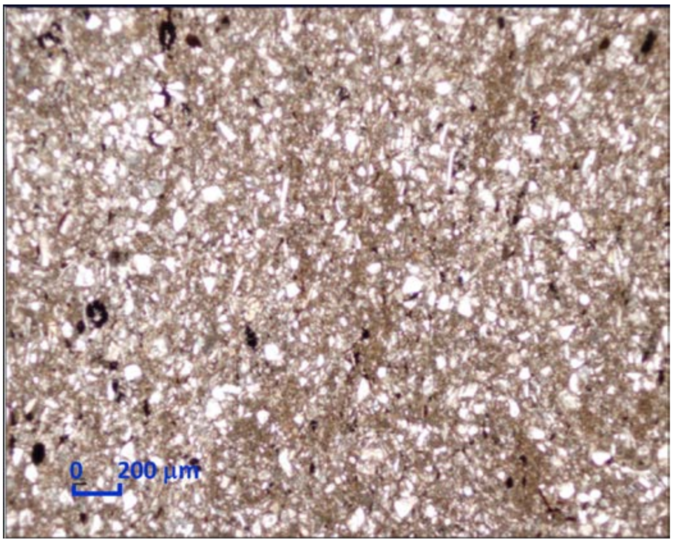


Figure 13. Homogeneous texture in thin section: wacky texture, composed of sand-sized quartz grains with fine-grained cemented matrix

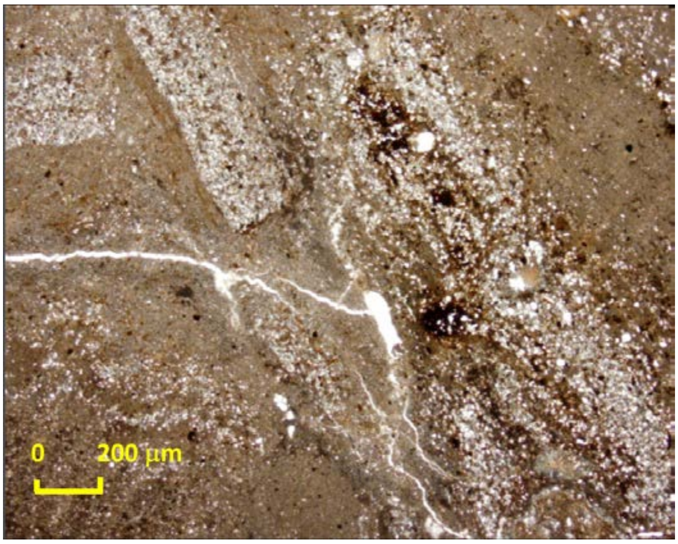


Figure 14. Heterogeneous texture in thin section: heterogeneous muddy- predominant texture.

The most distinctive features that classify homogeneous textures are grain-size distribution that can be coarse (sandy) or fine (muddy), or presence of fine matrix between coarse clasts (wacky). Fine grained matrix can be bonded either by micrite or sparite crystals or both. Matrix may also be indurated but not-cemented, composed by silt and clay without carbonate cement. The heterogeneous textures are characterized by the presence of clusters of either coarse grains or fine grained-matrix

All the samples were tested using a standard slaking test to characterize their durability. The procedure followed was the Slake Durability Test (Franklin and Chandra, 1972) up to five cycles (Figures 15 and 16, and table 2).

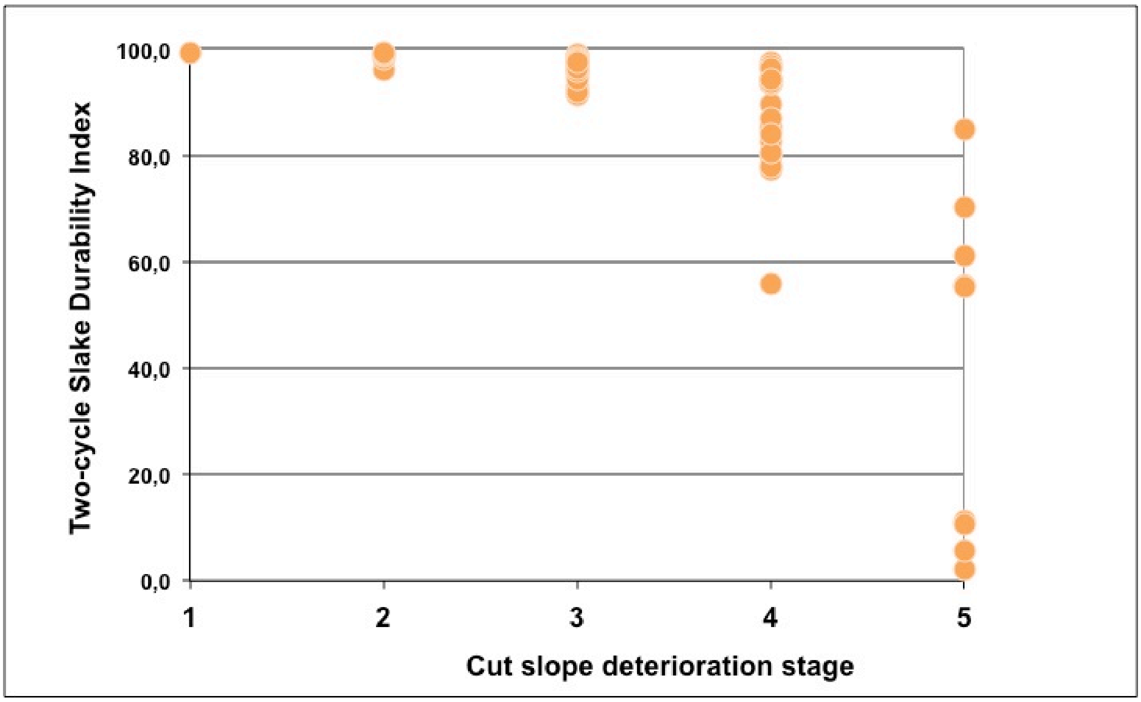


Figure 15. Two-cycle Slake Durability Index (SDI) of rock samples taken from cut slopes showing different deterioration stages (Fig. 10).

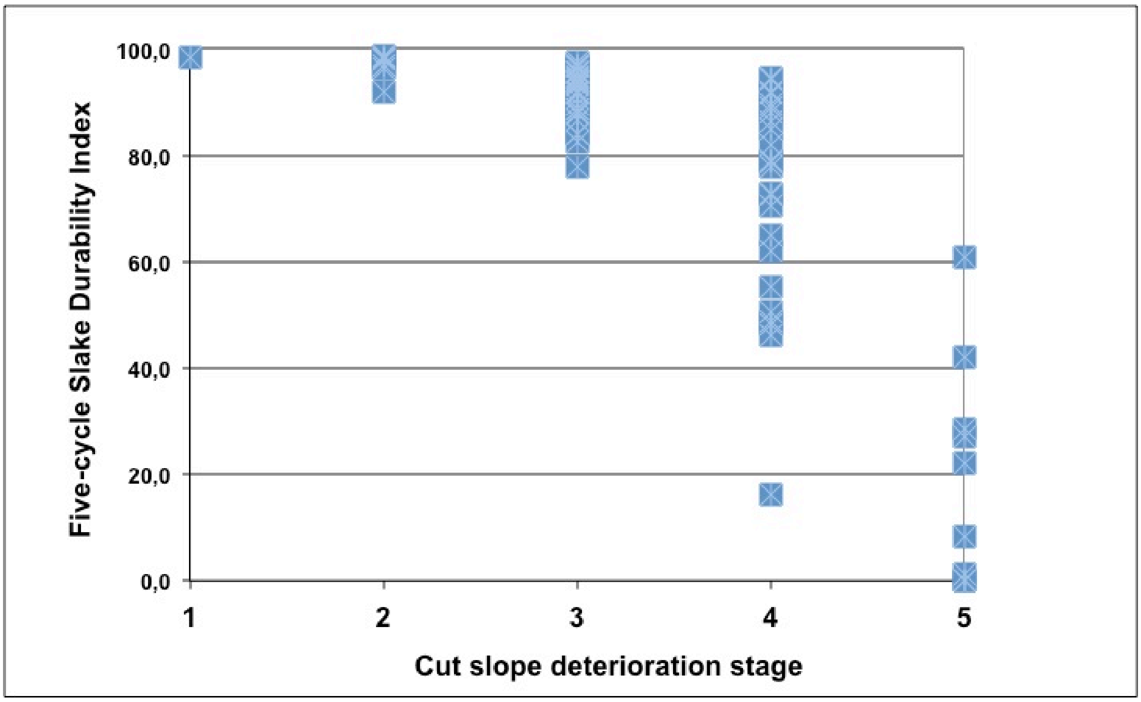


Figure 16. Five-cycle Slake Durability Index (SDI) of rock samples taken from cut slopes showing different deterioration stages (Fig. 10).

Samples extracted from cut slopes classified as deterioration stages 1 and 2 have homogeneous coarse and sandy wacke texture and display a Slake Durability Index (SDI) higher than 90% for the two-cycle test. These samples correspond to wackestones, with a high content of sandy grains and, commonly, a grain-supported texture, and carbonate bonding. Conversely, samples displaying two-cycle SDI smaller than

60% were obtained from cut slopes with deterioration stages 4 or 5. These samples correspond to rock with both homogeneous and heterogeneous muddy textures (Martínez-Bofill et al. 2008).

| Sample | Two cycle SDI | Five cycle SDI | Cut Slope Stage | | Sample | Two cycle SDI | Five cycle SDI | Cut Slope Stage |
|---|---|---|---|---|---|---|---|---|
| A-2.1 m1 | 2,1 | 0,0 | 5 | | C-25.5 m2 | 95,9 | 91,9 | 3 |
| A-2.1 m2 | 5,7 | 0,0 | 5 | | C-25.7 m1 | 61,2 | 28,6 | 5 |
| A-2.3 | 94,4 | 89,5 | 4 | | C-25.7 m2 | 85,0 | 60,9 | 5 |
| A-2.5 | 84,8 | 72,6 | 4 | | C-25.9 | 93,4 | 78,6 | 4 |
| A-2.6 | 97,6 | 94,5 | 4 | | C-55.1 m1 | 99,0 | 98,2 | 2 |
| A-2.7 | 89,5 | 77,7 | 4 | | C-55.1 m2 | 94,9 | 89,5 | 3 |
| A-2.8 | 93,4 | 79,1 | 4 | | C-55.1 m3 | 80,4 | 48,9 | 4 |
| A-2a.2 | 82,6 | 65,0 | 4 | | L-301.1 m1 | 70,3 | 42,1 | 5 |
| C-154.1 m1 | 98,6 | 96,7 | 3 | | L-301.2 m1 | 91,2 | 84,0 | 3 |
| C-16.1 m1 | 96,2 | 91,6 | 4 | | L-301.2 m2 | 96,6 | 93,0 | 3 |
| C-16.2 | 96,9 | 94,3 | 4 | | C-16.1 m2 | 99,1 | 98,5 | 1 |
| C-16.3 | 94,3 | 88,1 | 4 | | C-16.8 | 88,2 | 74,2 | 4 |
| C-16.4 m1 | 55,4 | 22,1 | 5 | | C-25.6 | 93,6 | 81,9 | 4 |
| C-16.4 m2 | 77,1 | 48,3 | 4 | | C-25.8 | 84,0 | 46,1 | 4 |
| C-16.4 m3 | 96,1 | 91,8 | 2 | | IM-2 | 97,3 | 94,1 | 3 |
| C-16.6 | 55,1 | 27,2 | 5 | | IM-3 | 97,5 | 94,1 | 3 |
| C-16.7 | 85,5 | 70,6 | 4 | | IM-5 | 95,8 | 90,6 | 3 |
| C-17.1 | 98,6 | 96,8 | 3 | | IM-6 | 96,9 | 93,5 | 3 |
| C-17.2 | 97,7 | 95,0 | 3 | | IM-8 | 96,2 | 91,9 | 4 |
| C-17.3 | 98,9 | 97,4 | 3 | | IM-9 | 92,9 | 86,7 | 3 |
| C-17.4 | 95,9 | 87,7 | 3 | | IM-11 | 92,0 | 88,1 | 3 |
| C-17.5 | 97,7 | 94,2 | 3 | | IM-12 | 95,5 | 91,7 | 3 |
| C-25.1 | 94,7 | 86,5 | 4 | | IM-13 | 92,7 | 77,8 | 3 |
| C-25.10 | 78,0 | 62,0 | 4 | | IM-15 | 98,0 | 96,7 | 3 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| C-25.11 | 11,1 | 8,4 | 5 | | IM-16 | 97,4 | 95,3 | 3 |
| C-25.12 m1 | 86,8 | 72,9 | 4 | | IM-17 | 98,9 | 98,2 | 2 |
| C-25.12 m2 | 94,2 | 89,0 | 4 | | IM-18 | 94,3 | 84,8 | 4 |
| C-25.13 | 98,3 | 96,9 | 3 | | OM-2 | 91,4 | 82,6 | 3 |
| C-25.14 m1 | 99,2 | 98,5 | 2 | | OM-5 | 91,8 | 84,0 | 3 |
| C-25.15 m1 | 98,2 | 96,2 | 2 | | OM-6 | 97,9 | 95,7 | 3 |
| C-25.16 | 79,8 | 50,5 | 4 | | OM-8 | 97,2 | 93,8 | 3 |
| C-25.17 | 10,5 | 1,2 | 5 | | OM-9 | 97,5 | 93,9 | 3 |
| C-25.2 | 96,2 | 88,8 | 3 | | OM-10 | 94,4 | 88,7 | 3 |
| C-25.3 | 98,5 | 96,8 | 2 | | OM-12 | 97,8 | 95,7 | 3 |
| C-25.4 m1 | 55,9 | 16,3 | 4 | | OM-13 | 95,9 | 92,0 | 3 |
| C-25.4 m2 | 97,1 | 94,7 | 3 | | OM-15 | 96,3 | 91,7 | 3 |
| C-25.5 m1 | 77,9 | 55,3 | 4 | | OM-18 | 99,3 | 98,6 | 2 |
| | | | | | OM-19 | 97,6 | 93,3 | 3 |

Table 2. Two-cycle and five-cycle Slake Durability Indexes (SDI) of samples collected in the studied cut slopes and their deterioration stages

However, Figs 15 and 16 show that no unique SDI range of values can be assigned to a specific deterioration stage. Despite the fact that several classification schemes consider those rocks displaying two-cycle SDI over 80 as durable rocks (Franklin and Dusseault, 1989; Sadisun et al. 2005; Santi, 2006), in our study area high SDI values do not guarantee the presence of intact slopes on the mid-long term. In fact, two thirds of the tested samples yielded two-cycle SDI over 80%. Figure 15 shows that samples extracted from cuts with deterioration stages 3 and 4 have yielded two-cycle SDI values ranging from 98.9 to 91.2 and 97.6 to 77.1, respectively. High values (>90%) of the SDI may also be found in cuts with deterioration stages 1 to 4, indicating that in the study area, the SDI is unable to adequately predict whether any particular slope will evolve towards deterioration stage 3 and 4, or it will remain unweathered. Such a lack of sensitivity of the two-cycle SDT to the rock durability (here, to the cut slope behaviour) has been observed by several researchers (Taylor, 1988; Moon and Beattie, 1995; Gökçeoglu et al 2000; Erguler and Shakoor, 2009).

Finally, the cut slope degradation stages have been contrasted against the textural composition of their exposed argillaceous rocks. The results have been split considering homogeneous and heterogeneous rock textures respectively (Figures 17 and 18).

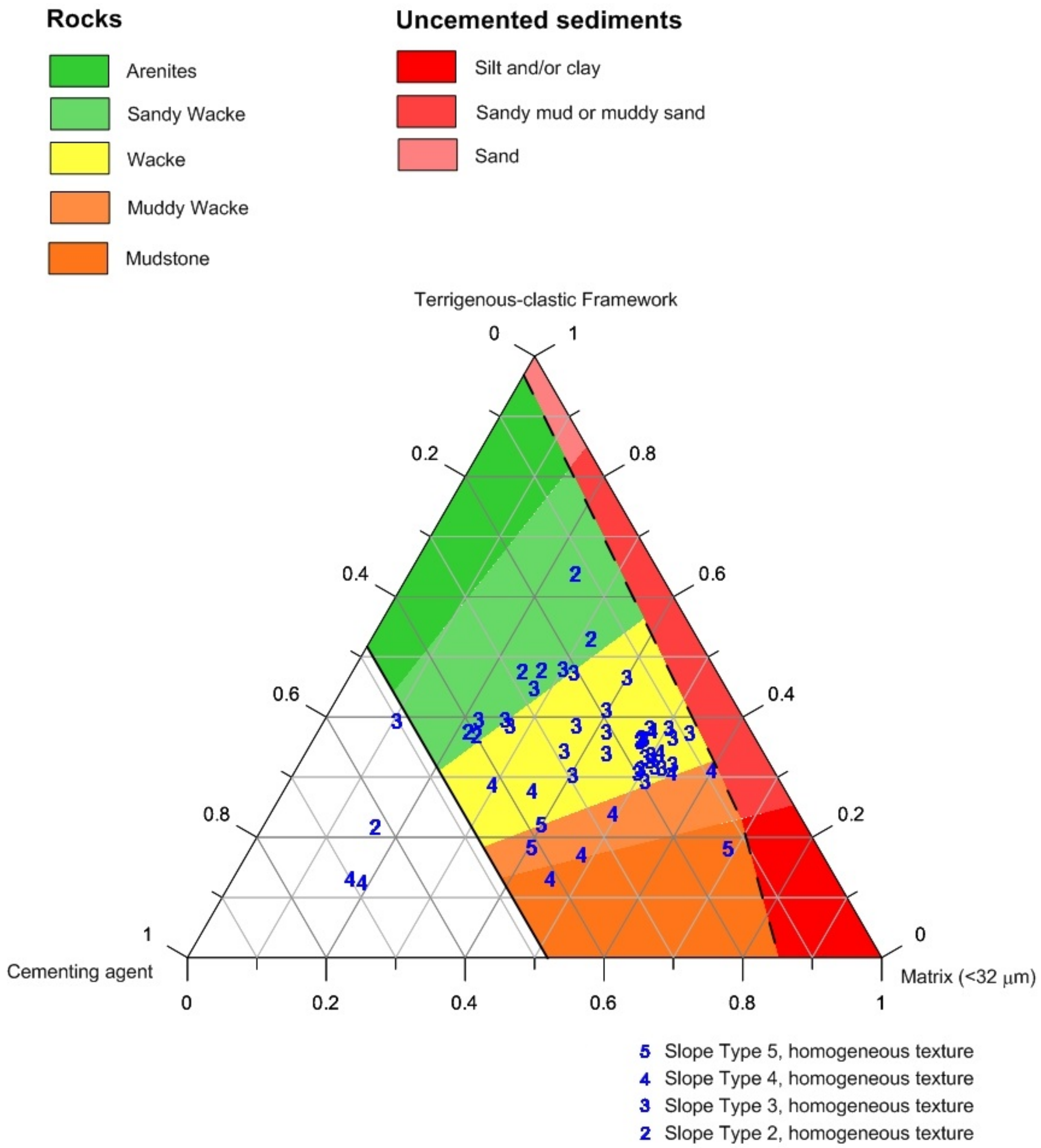


Fig. 17. Distribution of samples showing homogeneous texture from the analyzed cutslopes and their association to the slope deterioration stages (Fig. 10) plotted on the classification scheme proposed in this paper.

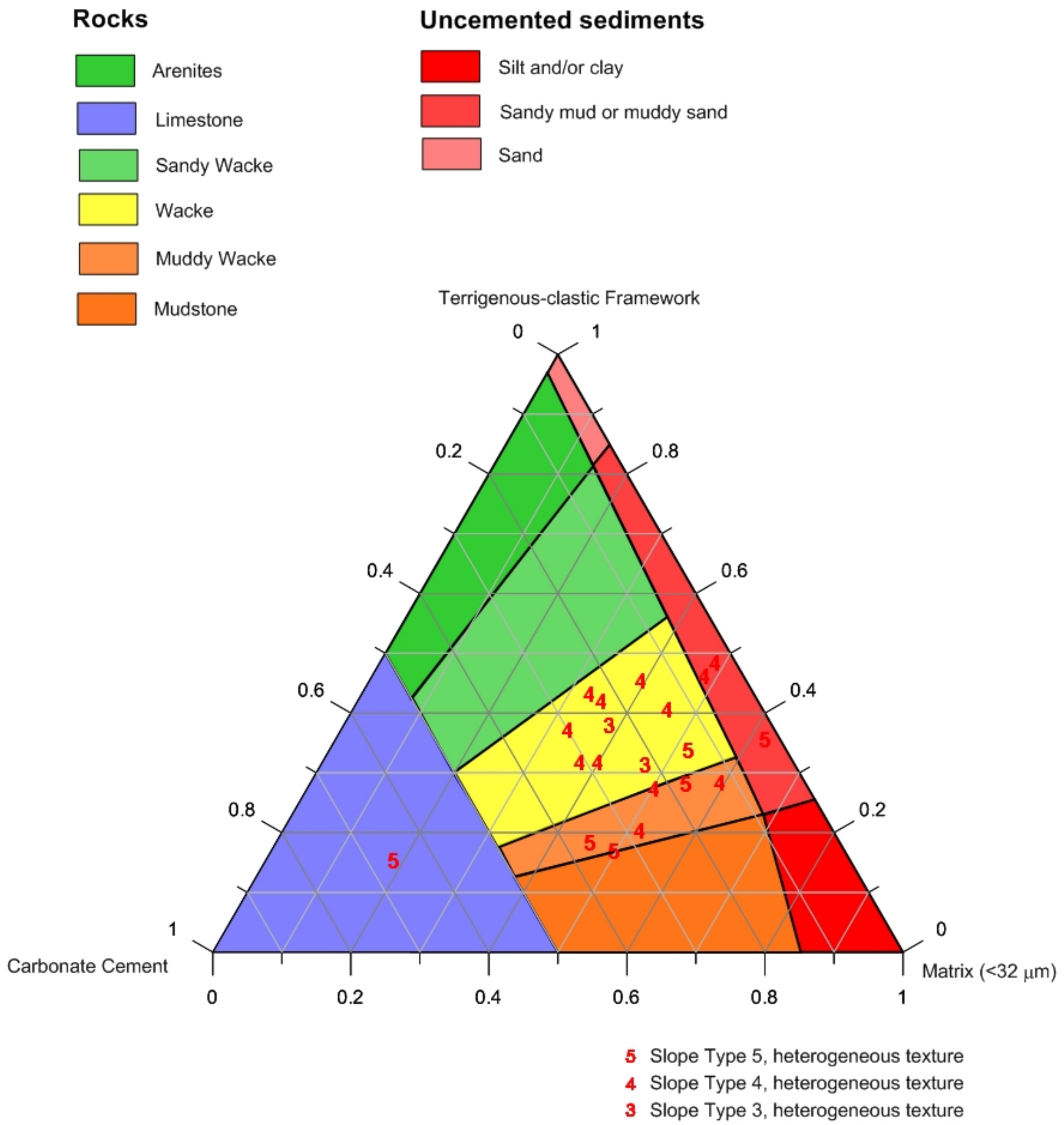


Fig. 18. Distribution of the samples showing heterogeneous texture from the analyzed cutslopes and their relation to the slope deterioration stages (Fig. 10) plotted on the classification scheme proposed in this paper.

Slopes excavated in sandy wackes consistently show few deterioration features while the slopes excavated in mudstones and muddy wackes deteriorate easily and are highly erodible and unstable. In that respect, the texturally homogeneous argillaceous rocks (Figure 17) show a contrasting response and a reasonable correspondence with the deterioration stage of the excavated slopes. Texturally heterogeneous slopes (Figure 18) display a higher degradability for similar textures. It is suggestive that heterogeneity, and particular the uneven distribution of the grain favours on one hand, the existence of preferential flow paths (high connected porosity or permeability) of the weathering agents and on the other hand, the inability of the cementing agents for accessing the fine-grained clusters.

In figure 17, two samples composed of about 80% of total calcium carbonate were studied further to find a more in-depth explanation. As mentioned in the previous section, the main assumption in the procedure followed is that all the carbonate content of the fine-grained matrix is a cementing agent. Figure 19 is an image obtained with a Scanning Electron Microscope with Energy Dispersive X-ray Spectroscopy. It shows well developed dolomite crystals mostly ranging between 2 and 12 μm in size. These crystals have replaced previously existing calcite crystals, reaction that produces a reduction of the volume with the subsequent loss of the effectiveness of the bonding action.

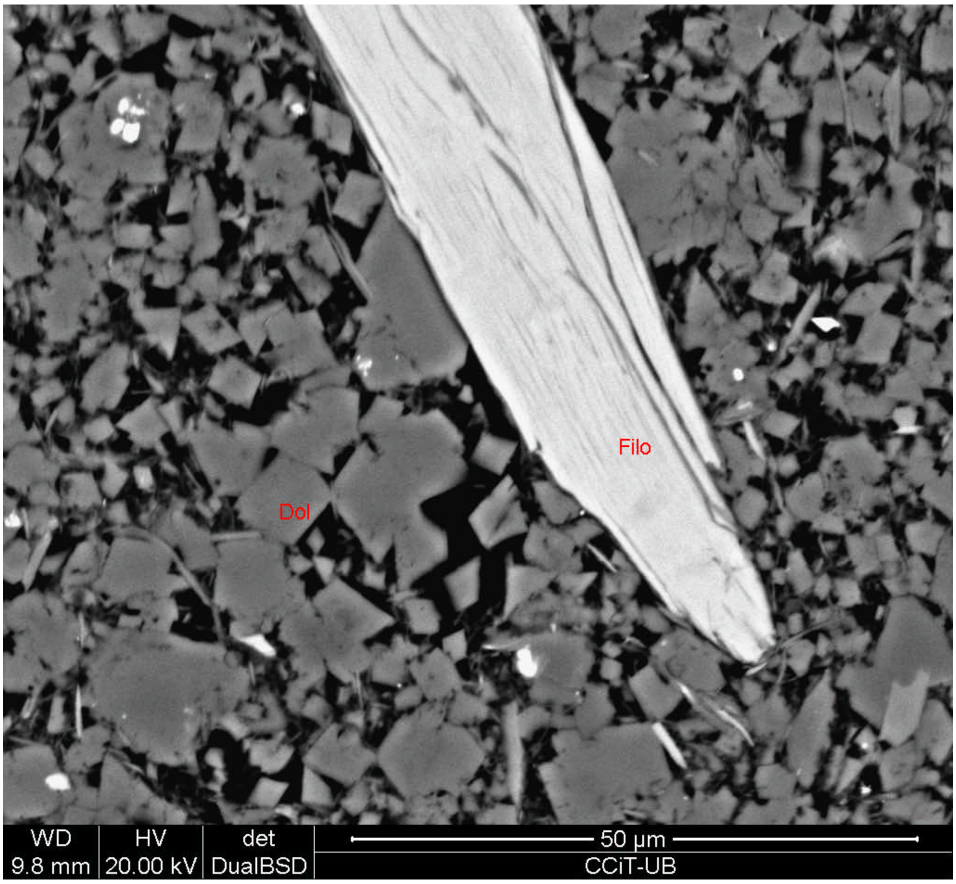


Figure 19. Scanning Electron Microscope image of well-developed dolomite crystals (Dol) surrounding a crystal of phyllosilicate (Filo). This image is from one of the samples shown in the lower left-edge (labeled with number 4) in Figure 11.

This case shows that while the proposed classification scheme provides a good indicator of likely road cut performance there are additional factors that can influence the actual performance.

One must take into account that the excavation process disturbs the rock mass by releasing confinement and causing expansive recovery (Gerber and Scheidegger, 1969; Nichols, 1980) and exposes it to the environmental conditions particularly to moisture and temperature changes. Other well-known factors such as the connected porosity, presence of the expansive or soluble minerals, which have been identified as influencing durability, have not been considered in the classification. Therefore, it will require further analysis and development. Despite of this, texturally-homogeneous argillaceous rocks have shown a satisfactory correspondence with the long-term performance of the excavated slopes.

The analysis of the Figures 17 and 18 also highlights that the relationship between cement content and durability is complex. Surprisingly, changes in the cement content of the rocks per se are not reflected in the nature and quantity of deterioration features observed in the excavated slopes. Figure 17 shows that the increase in content of the calcium carbonate cement within the different types of wackestones does not result in an increase of the durability of the corresponding excavated slope. On the other hand, Figure 17 suggests that it is the ratio between the clastic framework and the fine-grained matrix that actually controls the durability of the argillaceous rocks.

Based on this, we interpret that the effectiveness of the bonding between particles depends on the amount of matrix and, particularly on the content of phyllosilicate minerals (clay minerals, mica minerals, chlorite). The efficacy of the cementing agent in sandstones and sandy wackestones for creating strong bonds between the grains is high. This is because the bond is generated as grain-to-grain connection. In wackestones, muddy wackestones and mudstones the matrix content (i.e. phyllosilicates) is high. In this case bonding takes place between grains of the clastic framework, phyllosilicate minerals or between both. Degradation of the argillaceous rock may occur by splitting apart sheets of the phyllosilicate minerals through their exfoliation planes (Figure 20) which are held to one another by weak residual forces, Van der Waals, hydrogen bonds and cations (Thorez, 1975; Weaver, 1989). In this case, rock deterioration can only be prevented by a cementing agent able to generate effective bonds between the grains of the clastic framework and/or around the phyllosilicate minerals.

Figure 20.Interpretative sketch of the rock disaggregation. Left: sand-size calcite crystals (yellow) bonding both clasts (white) and phyllosilicates (green); Right: disaggregation of the rock is facilitated by the presence of weak phyllosilicate layers bonds

FINAL REMARKS

Several researchers agree on that the texture and the mineralogical composition of the argillaceous rocks are critical parameters controlling their durability (i.e. Gökçeoglu et al. 2000; Sadisun et al 2005). These two components condition the effectiveness of the weathering processes in changing the intrinsic characteristics of the argillaceous rocks such as the mineralogy, porosity, particle cohesion and the development of microfractures. Other parameters such as the geological history (degree of fracturing, stresses) and the stress release mechanisms must also exert a strong influence (Cripps & Czerewecko, 2006).

The textural-based classification scheme of the argillaceous rocks presented here aims at effectively accounting for the texture and unlike other classification schemes, the cementing agent has been considered. Three components form the basis for the classification: the clastic framework, the fine-grained matrix and the cement content.

To implement this classification either quantitative petrographical or mineralogical analysis is required to determine the textural components. In the samples analyzed in the study areas in Spain, petrographic analysis using an optical microscope and supported with semi-quantitative Rietveld mineralogical analysis based on X-ray powder diffraction have yielded consistent results. These procedure might appear time-consuming and expensive for the durability analyses of the rock. However, this drawback is not more restrictive than other mechanical analysis (i.e. UCS, triaxial tests) routinely performed in engineering projects.

The analysis of the behavior of the argillaceous rocks in different excavated slopes in Spain shows that road cuts in sandy wackes consistently show few deterioration features while the slopes excavated in muddy wackes and mudstones deteriorate easily, are highly erodible, and produce frequent falls. Texturally homogeneous sandy wackes, wackes and muddy wackes, are mostly associated with slope deterioration stages 2, 3, and 4-5, respectively.

The relationship between the cement content and the durability of the rock is complex. We have found that deterioration is mainly prevented by bonding of the grains of the clastic framework. The increase of matrix content and, particularly the presence of phyllosilicate minerals, makes bonding inefficient. Because of this, we conclude that the ratio between the clastic framework and the fine-grained matrix exerts a strong control on the durability of the argillaceous rock. The increase of cementing agent beyond a certain amount does not result in an improvement of the durability.

Argillaceous rocks showing heterogeneous textures are less durable. We interpret that heterogeneity favours the existence of preferential flow paths where the weathering agents can penetrate more easily and the presence of fine-grained clusters where the cementing agents are less effective.

The proposed classification scheme provides a good first order estimate of the long-term behaviour of argillaceous rock cuts but there are still shortcomings that need to be improved. There are a variety of factors that are not included as the presence of either expansive or soluble minerals, the stress history of the rock, the effect of textural heterogeneity, among others. The influence on durability of the different types of cementing agents (calcite, silica, iron oxide, etc.) also has to be considered in future investigations

In the study area the proposed classification scheme performs more satisfactorily than the two-cycle SDT in assessing the potential of the slopes to deterioration. Rock samples having two-cycle SDT values higher than 90% may are associated to cuts showing a wide range of deterioration stages (from stage 2 to 4).

REFERENCES


Alonso EE, Pineda JA (2006). Weathering and degradation of shales: experimental observations and models of degradation. VIth South American Conference on Rock Mechanics, Cartagena de Indias-Colombia. Colmenares & Montero Eds., pp. 249-296

ACI-American Concrete Institute. (1997). State-of-the-Art Report on Soil Cement. ACI230.1R-90

Bish DL, Post JE (1989). Modern Powder Diffraction, MSA Reviews in Mineralogy 20, Washington, Mineralogical Association of America, 384 p.

Blatt H (1982). Sedimentary petrology: WH Freeman and Company, San Francisco, 564 pp.

Bjerrum L (1967) Progressive failure in slopes of overconsolidated plastic clay and clay shales. J.Soil Mech. & Found. Division, ASCE, Vol 93, pp.3-49.

Calcaterra, D, Parise M (2010). Weathering as a predisposing factor to slope movements: an introduction. In D. Calcaterra & M. Parise (Eds.). *Weathering as a predisposing factor to slope movement.* Geological Society, London, Engineering Geology Special Publication 23:1-4. DOI: 10.1144/EGSP23.1

Cripps JC, Czerewko MA (2006). The implications of diagenetic history and weathering on the engineering behaviour of mudrocks. In 10th Congress of the International Association of Engineering Geology and the Environment, Nottingham.

Chandler RJ (2010). Stiff sedimentary clays: geological origins and engineering properties, Géotechnique, 60: 891-902

Conway JA, Sloane NJA (1993). Sphere packings, lattices and groups. Springer-Verlag. New York.

Dick JC, Shakoor A (1997). Predicting the durability of mudrocks from geological characteristics of mudrocks: in Santi, P. and Shakoor, A., eds., Assoc. Eng. Geol., Special Publication No. 9, pp. 89-105

Dott RH (1964). Wackstone, graywacke and matrix = what approach to inmature sanstone classification?. Journal of sedimentary petrology. Num 34. 625-632 pp

Erguler ZA, Shakoor A. (2009). Quantification of fragment size distribution of clay-bearing rocks after slake durability testing. Environmental and Engineering Geoscience 15: 81-89

Erguler ZA, Ulusay, R. (2009). Assessment of physical disintegration characteristics of clay-bearing rocks: disintegration index test and a new durability classification chart. Engineering Geology, 105: 11-19

Folk RL (1954). The distinction between grain size and mineral composition in sedimentary rock nomenclature: Journal of Geology, 62: 344-359.

Folk RL (19809. Petrology of sedimentary rocks: Austin, Texas, Hemphill's Bookstore, 170 pp.

Franklin JA, Chandra R (1972). The slake durability test. International Journal of Rock Mechanics and Mining Science & Geomechanics Abstracts, 9, 325-328.

Franklin JA (1983). Evaluation of Shales for Construction Projects: an Ontario shale rating system. Report RR29 Research and Development Branch. Ministry of Transportation and Research. Toronto

Franklin JA, Dusseault MB (1989). Rock Engineering. Mc Graw Hill Inc. New York. 600pp.

Gens A (2013). On the hydromechanical behaviour of argillaceous hard soils-weak rocks. Proceedings of the 15th European Conference on Soil Mechanics and Geotechnical Engineering – Geotechnics of Hard Soils – Weak Rocks (Part 4). A. Anagnostopoulos et al. (Eds.). IOS Press. pp. 71-118

Gerber E, Scheidegger AE (1969). Stress-induce weathering of rock masses. Eclogae Gelogicae Helvetiae 62: 401-416

Gökçeoglu C, Ulusay R, Sönmez H (2000). Factors affecting the durability of selected weak and clay-earing rocks from Turkey, with particular emphasis on the influence of the number of drying and wetting cycles. Engineering Geology 57: 215-237

Grattan-Bellew PE, Eden W J. (1975). Concrete deterioration and floor heave due to biogeochemical weathering of underlying shale. Canadian Geotechnical Journal, 12: 372 - 378.

Hallsworth CR, Knox RWO'B (1999). BGS Rock Classification Scheme. Volume 3. Classification of sediments and sedimentary rocks. British Geological Survey. Research Report number rr 99-03. Nottingham UK. 44 pp.

Hawkins AB (2000). General Report: The nature of hard soils/soft rocks, The Geotechnics of Hard Soils – Soft Rocks (A. Evangelista, L. Picarelli, eds.) Balkema, Rotterdam. Vol.3: 1391-1402

Johnston IW, Novello EA (1993). Soft rocks in the geotechnical spectrum, Geotechnical Engineering of Hard Soils-Soft Rocks (A. Anagnostopoulos et al., eds.),
Balkema, Rotterdam. Vol.1: 177-183.

Kornprobst J (2003) Metamorphic rocks and their geodynamic significance. A petrological handbook. Kluwer Academic Publishers. 205 pp.

Krynine PD (1948), The megascopic study and field classification of sedimentary rocks: Journal of Geology, 56:130-165

Marinos PG (1997). General Repot Session 1: Hard soils – soft rocks: Geological features with special emphasis to soft rocks, Geotechnical Engineering of Hard Soils- Soft Rocks (A. Anagnostopoulos et al., eds.), Balkema, Rotterdam. Vol. 3: 1807-1826

Martinez-Bofill J, Corominas J, Soler A (2004). Behaviour of the weak rock cutslopes and their characterization using the results of the Slake Durability Test. In Lecture Notes in Earth Sciences. 104. Engineering Geology for Infrastructure Planing in Europe, pp. 405-413.

Martinez-Bofill J, Corominas J, Soler A (2008). Analysis of the relationship between durability and petrological characteristics of weak rocks. Euroengeo. Proceedings of the II European Conference of International Association for Engineering Geology. Madrid

Martinez-Bofill J (2011). Alterabilidad de limolitas, arcillitas y margas. Aplicación a la estabilidad de desmontes y excavaciones. PhD Thesis. Universitat Politèccnica de Catalunya. 427 pp.

Mitchell JK (1993). Fundamentals of soil behavior. John Wiley & Sons, New York. 437 pp.

Moon VG, Beattie AG (1995). Textural and microstructural influences on the durability of Waikato coal measures mudrocks. Quaterly Journal of Engineering Geology, 28: 303-312

Morgenstern N (1974). Classification of Argillaceous Soils and Rocks. Journal of the Geotechnical Engineering Division, Vol. 100 (10): 1137-1156

Nichols TC (1980). Rebound its nature and effect on engineering works. Quaterly Journal of Engineering Geology, 13: 133-152

Nicholson DT (2004). Hazard assessment for progressive, weathering-related breakdown of excavated rockslopes. Quarterly Journal of Engineering Geology and Hydrogeology, 37, 327–346

Nickmann M, Spaun G, Thuro K (2006). Engineering geological classification of weak rocks. In 10th Congress of the International Association of Engineering Geology and the Environment, Paper number 492, Nottingham

Nickmann M, Sailer S, Ljubesic J, Thuro K (2010). Engineering geological investigations into the border between hard and weak rocks. Geologically Active – Williams et al. (eds). Taylor & Francis Group, London. pp. 2265-2272

Pettijohn FJ, Potter PE, Siever R. (1972). Sand and Sandstone. Springer-Verlag, Nueva York, 618 pp

Pineda JA, Alonso EE, Romero R (2014). Environmental degradation of claystones. Geotechnique, 64: 64-82

Potter PE, Maynard JB, Depetris PJ (2005). Mud and mudstones. Springer-Verlag, Berlin. 308 pp.

Potts PJ (1992). X-ray fluorescence analysis: principles and practice of wavelength dispersive spectrometry. In Potts PJ (Ed) Handbook of silicate rock analyses. p. 226-285

Quigley RM, Vogan RW (1970). Black shale heaving at Ottawa, Canada. Canadian Geotechnical Journal, 7: 106-112

Russell DJ (1981). Controls on shale durability: the response of two Ordovician shales in the slake durability test. Canadian Geotechnical Journal,19: 1-13,

Sadisun IA, Shimada H, Ichinose M, Matsui K. (2005). Study on the physical disintegration characteristics of Subang claystone subjected to a modified slaking index test. Geotechnical and Geological Engineering, 23: 199-218.

Santi P (1998). Improving Jar Slake, Slake index, and Slake Durability Tests for shales. Environmental & Engineering Geoscience, 4: 385-396

Santi P (2006). Field methods for characterizing weak rocks for engineering. Environmental & Engineering Geoscience, 12: 1-11

Simpson B (2010). Engineering in stiff sedimentary clays. Géotechnique, 60: 903-911.

Taylor RK (1988). Coal Measures mudrocks: composition, classification and weathering processes. Quarterly Journal of Engineering Geology and Hydrogeology, 21, 85-99.

Terzaghi K, Peck RB (1967). Soil Mechanics in Engineering Practice. Wiley, New York, 729 pp.

Terzaghi K, Peck RB, Mesri G (1996). Soil Mechanics in Engineering Practice, 3rd ed., John Wiley & Sons, New York. Winterkorn, 549 pp.

Thorez J (1975). Phyllosilicates and Clay Minerals: A laboratory handbook for their X-Ray diffraction Analysis. G. Lelotte. California University. 579 pp.

USACE (1994). Soil Stabilization for Pavements. Joint Departments of the Army and Air Force, USA, TM 5-822-14/AFMAN 32-8010

U.S. Geological Survey, USGS, (2004). North American Geologic-Map Data Model Science Language Technical Team, 2004b, Report on progress to develop a North American science-language standard for digital geologic-map databases; Appendix C1 – Sedimentary materials: Science language for their classification, description, and interpretation in digital geologic-map databases; Version 1.0 (12/18/2004), *in* Soller, D.R., ed., Digital Mapping Techniques ’04—Workshop Proceedings: U.S. Geological Survey Open-File Report 2004-1451, 595 p. Appendix C1 accessed at http://pubs.usgs.gov/of/2004/1451/sltt/appendixC/appendixC_pdf.zip.

Ward CR, Nunt-jaruwong S, Swanson J. (2005). Use of mineralogical analysis in geotechnical assessment of rock strata for coal mining. International Journal of Coal Geology, 64: 156-171

Weaver CE (1989). Clay, muds and shales. Developments in Sedimentology, 44. Elsevier Science Publishers B.V. Amsterdam, The Netherlands. 809 pp.

Williams H, Turner FJ, Gilbert CM (1982) Petrography, An Introduction to the Study of Rocks in Thin Section: W.H. Freeman and Co., San Francisco, 626p.

Wood LE Deo P (1975). A suggested system for classifying shale materials form embankments. Bulletin of the Association of Engineering Geologists, 12: 39-55

Young RA (1993). The Rietveld Method. International Union Crystallography, Oxford University Press, 298 p. New York.